

Stochastic Cooling of the Recycler Antiproton Stack Momentum Spread Including Intrabeam Scattering and Barrier Buckets

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1. Motivation

The effect of intrabeam scattering in the Recycler ring is to increase the momentum spread of the antiproton stack at a rate which depends on the momentum spread, transverse emittance, and the instantaneous beam current. The intrabeam scattering growth rate is proportional to the beam current. Assuming a constant transverse emittance, the shape of the intrabeam scattering growth rate on momentum spread is quite nonlinear.

A barrier bucket RF system is planned for the Recycler ring which can be used to segment cooled and recycled antiprotons into separate portions of the azimuth, facilitating the recycling and Tevatron injection missions of the ring. The interesting feature of this system is the ability to adiabatically adjust the distribution shape of the beam around the accelerator. In particular, a ring completely filled except for a single gap region can be manipulated so as to tailor the momentum spread or pulse length of the antiproton beam.

The purpose of momentum cooling in the Recycler is to fight the ravages of intrabeam scattering. The ability of stochastic cooling to combat this growth is quite limited. Therefore, it is important to understand the cooling scenario so as to assure that the proposed cooling system is adequate.

In the paper it will be pointed out that considerable improvement in the ability of stochastic cooling to shrink and maintain the momentum spread of the Recycler antiproton beam can be accomplished by using the barrier bucket RF system to maintain a constant momentum spread by compressing the pulse length of the beam. This argument is applied to the anticipated antiproton stacking scenario.

2. Intrabeam Scattering

Extensive calculations of intrabeam scattering in the Recycler ring (Colestock, 1996) indicate that the momentum growth rate for a fixed 95% invariant transverse emittance of 10π mmmr is quite fast for the anticipated beam currents. In addition, the rate of increase in growth rate with diminishing rms momentum spread is very well described by the approximation

$$\alpha_{\text{IBS}} = \frac{k}{\left(\frac{\sigma_p}{P}\right)^3}, \quad (2.1)$$

where $k=1.3 \times 10^{-11} \text{ hr}^{-1}$ at 100 mA of antiproton beam current. Both the calculated and fit dependencies of intrabeam scattering growth rate on rms momentum spread are plotted in figure 2.1. Note that a cooling system with a momentum cooling time of 1 hour can only reduce the rms momentum spread to approximately 2 MeV at the current of 100 mA. The engineering form of the equation can be written as

$$\alpha_{\text{IBS}}[\text{hr}^{-1}] = 0.093 \frac{I_b [\text{mA}]}{(\sigma_E [\text{MeV}])^3} \quad , \quad (2.2)$$

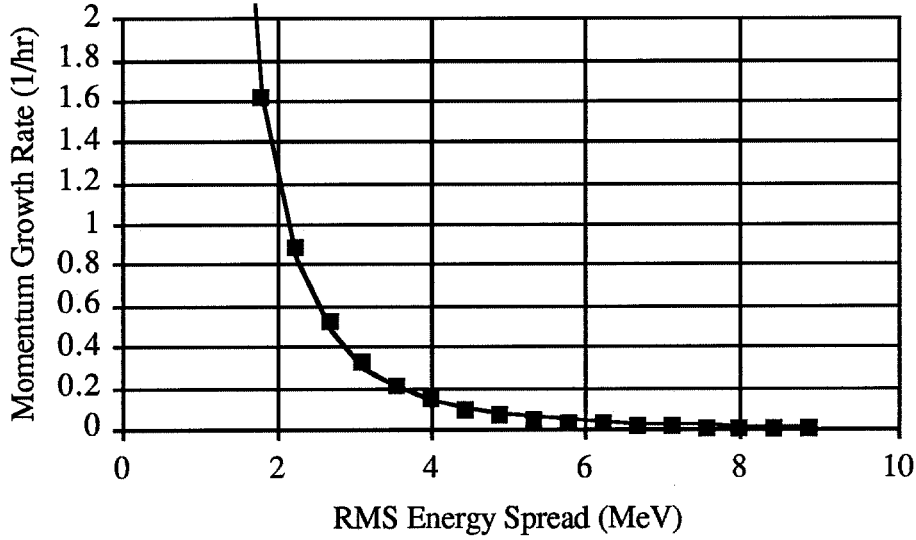


Figure 2.1: Calculated intrabeam scattering driven momentum growth rate in the Recycler ring as a function of momentum spread. The 95% invariant transverse emittance is 10π mmmr and the beam current in 100 mA (corresponding to a full turn antiproton intensity of 700×10^{10}). The points are calculated values while the line is the result of an inverse cubic fit.

3. Barrier Buckets

The invariant 95% longitudinal emittance A of an antiproton beam which has a distribution shape which is uniform azimuthally and Gaussian in energy is

$$A = 4T_p \sigma_e \quad , \quad (3.1)$$

where T_p is the current pulse length and σ_e is the rms energy spread. Using barrier voltage pulses generated by a broadband RF system, as shown in figure 3.1, the beam distribution can be molded to change the current pulse length while keeping the invariant longitudinal emittance constant. Of course, this requires that a compensating change in rms energy spread take place during the pulse compression or expansion process.

These barrier voltage pulses are the optimum waveform which can be used with broadband solid-state amplifiers. For a given maximum waveform voltage, a rectangular voltage pulse produces the maximum bucket height. If T is the voltage pulse length and V_0 is the voltage amplitude, the bucket half height $\Delta E_{1/2}$ is given by

$$\Delta E_{1/2} = \sqrt{\frac{T}{T_0} \frac{2\beta_r^2}{\eta} eV_0 E_0} \quad , \quad (3.2)$$

where T_0 is the revolution period, E_0 is the design energy, and η is the momentum compaction factor.

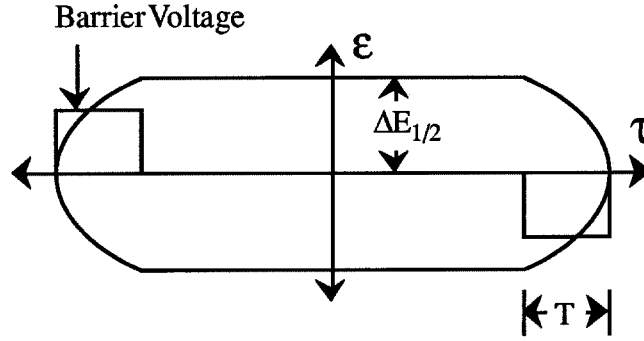


Figure 3.1: Sketch of a barrier bucket with the two voltage pulses that produce it.

For the Recycler ring a maximum voltage of 2 kV is anticipated. Given the other parameter values dictated by the lattice ($\eta = -0.0086831$, $T_0 = 11.126 \mu\text{sec}$) and beam energy ($\beta_r = 0.9945$, $E_0 = 8938 \text{ MeV}$), the dependence of bucket area on voltage amplitude and pulse length is described by the engineering equation

$$\Delta E_{1/2} [\text{MeV}] = \sqrt{183 T [\mu\text{s}] V_0 [\text{kV}]} \quad (3.3)$$

For instance, a pulse width of $0.5 \mu\text{sec}$ and a voltage of 2 kV generates a bucket with a half height of 13.5 MeV.

4. Stochastic Cooling

Using stochastic cooling to reduce the momentum spread of the Recycler antiproton beam, there are two basic feedback approaches which can be used. In filter cooling, the spread in revolution frequencies is observed with a longitudinal detector in order to deduce the energy distribution of the beam. In Palmer cooling, a horizontal pickup in a high dispersion area is used to measure the dispersive width of the beam in order to deduce the beam energy distribution. Both of these methods have their own relative strengths and weaknesses, and both suffer from a rather restrictive momentum aperture.

In filter cooling, the maximum momentum deviation which is stable within the cooling system is defined as that momentum which produces a revolution frequency shift with respect to the maximum revolution frequency harmonic in the system bandwidth of half of the revolution frequency. The relationship between frequency shift, frequency, and momentum error is described by the equation

$$\frac{\Delta f}{f} = \eta \frac{\Delta P}{P} = \frac{\eta}{\beta_r^2} \frac{\Delta E}{E} \quad (4.1)$$

The maximum frequency of the stochastic cooling system envisioned for the Recycler ring is 8 GHz. Table 4.1 summarizes the relevant parameters leading up to the theoretical momentum aperture of a filter cooling system.

Table 4.1: Parameter values which determine the momentum aperture of a filter momentum cooling system in the Recycler ring.

Parameter	Value
Maximum System Frequency (GHz)	8
Revolution Frequency (kHz)	89.88
Relativistic Velocity of the Beam	0.9945
Momentum Compaction	-0.0086831
Beam Energy (MeV)	8938
System Momentum Aperture (MeV)	5.7

In Palmer cooling, the criterion which determines the momentum acceptance of the system is the bad mixing between the pickup and kicker. It is necessary that the momentum compaction induced phase slip of an off-energy particle be within 90° of the design energy particles. For a fractional momentum error δ and revolution period T_0 , the phase slip (in radians) at the maximum system frequency f_{\max} is described by the formula

$$\Delta\theta = 2\pi f_{\max} T_0 \delta \eta \quad (4.2)$$

In equation (4.2) the implicit assumption is that the pickup and kicker are adjacent (like the Tevatron bunched beam stochastic cooling system), and the feedback system delays the signal for one turn. Solving for the energy aperture ΔE , assuming $\Delta\theta = \pi/4$ for extra phase margin, yields

$$\Delta E = \frac{\beta_r^2 E_0}{8 f_{\max} T_0 \eta} \quad (4.3)$$

If a particularly optimized chord is cut across the ring, the phase slip factor $T_0 \eta$ is reduced by a factor of 6.45. Table 4.2 contains the parameter values for the Recycler ring.

Table 4.2: Parameter values which determine the momentum aperture of a Palmer momentum cooling system in the Recycler ring.

Parameter	Value
Maximum System Frequency (GHz)	8
Revolution Period (μsec)	11.126
Relativistic Velocity of the Beam	0.9945
Momentum Compaction	-0.0086831
Beam Energy (MeV)	8938
System Momentum Aperture (MeV)	1.4
Improvement Factor Cutting a Chord	6.45
Momentum Aperture with Chord (MeV)	9.2

Therefore, even assuming a more conservative phase margin criterion, Palmer cooling has a more favorable momentum aperture. On the other hand, an insert with high dispersion and low beta is required to keep the electronic system gain and the signal-to-noise factor reasonable. At present no lattice solution for such an insert exists.

5. Cooling Scenario

The usage of the Recycler ring during the stacking process is shown in figure 5.1. Because of the low phase space density of the 20×10^{10} antiprotons injected from the Accumulator every hour, it is much more profitable to transfer the last stacked antiprotons (batch #7) after the Tevatron injection cycle is complete. For the sake of introducing the cooling of the recycled and stacked beams, they will initially be treated independently.

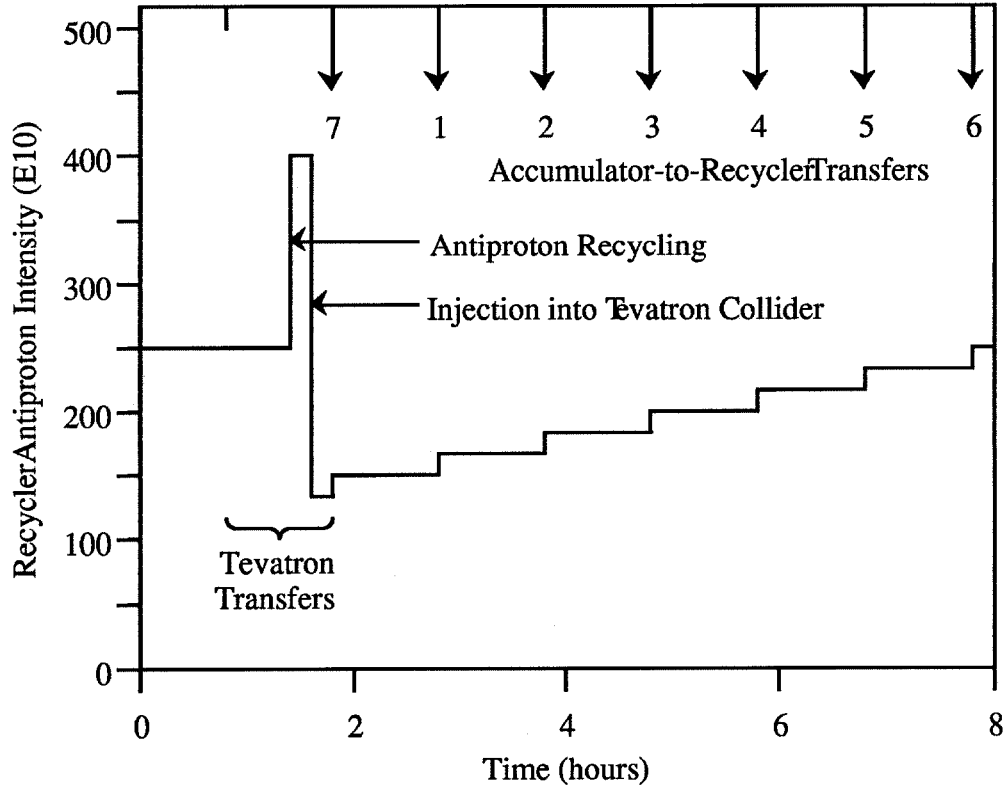


Figure 5.1: Recycler antiproton intensity as a function of time in a standard Tevatron Collider cycle.

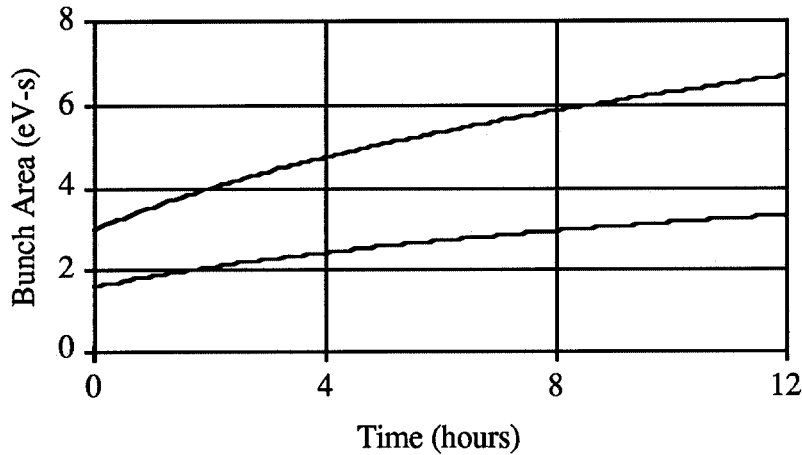


Figure 5.2: Simulation result of the proton (upper) and antiproton (lower) invariant 95% longitudinal emittances for Tevatron Collider Run II.

5.1. Recycling Antiprotons from the Tevatron

As can be seen in figure 5.2, the 95% invariant longitudinal emittance of the recycled antiproton bunches is at most 3 eV-sec at the end of a store. Since there are a total of 36 bunches, the total initial longitudinal emittance is approximately 108 eV-sec. The simulated emittance dilution in the deceleration process is approximately 10%. If the recycled beam is spread uniformly around the Recycler circumference, the diluted longitudinal emittance of 120 eV-sec corresponds to an energy spread of 2.7 MeV. The estimated antiproton intensity in this distribution is 148×10^{10} , which assumes an 80% deceleration efficiency from Tevatron low-beta.

The maximum energy spread which can be cooled will depend on whether Palmer or filter cooling will be employed in the Recycler. The most restrictive choice would be filter cooling, which in order to cool 95% of the beam would require an rms energy spread of less than 2.8 MeV. An rms energy spread of 2.7 MeV is used for the following calculations. Remember, this energy spread will be maintained by shrinking the length of the beam distribution with the barrier bucket RF system.

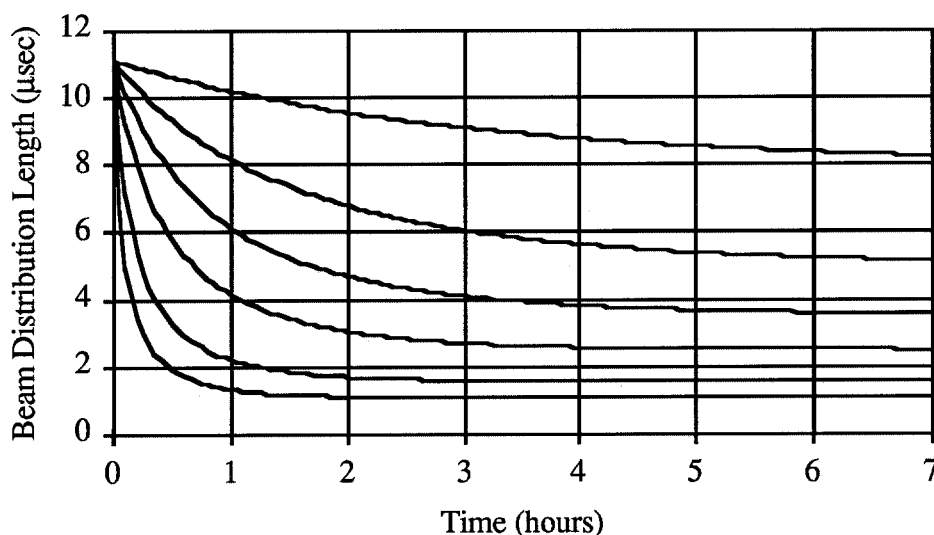


Figure 5.3: Simulation results of the evolution of longitudinal phase space assuming intrabeam scattering and stochastic cooling. The different curves correspond to different initial stochastic cooling times in the order 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom) hours.

Figure 5.3 shows the results of a simulation in which cooling and intrabeam scattering were applied to the antiproton beam distribution. In this figure the length of the beam distribution is plotted as a function of time. The dominant repercussion of this compression of the beam distribution, which maintains the momentum spread at a constant value, is to increase the instantaneous beam current. The time evolution of the instantaneous beam current is plotted in figure 5.4. The increase in beam current slows down the stochastic cooling system proportionally and increases the rate of intrabeam scattering induced momentum spread growth also proportionally. As shown in figure 5.5, another implication of reduced beam distribution length is reduced invariant 95% longitudinal emittance.

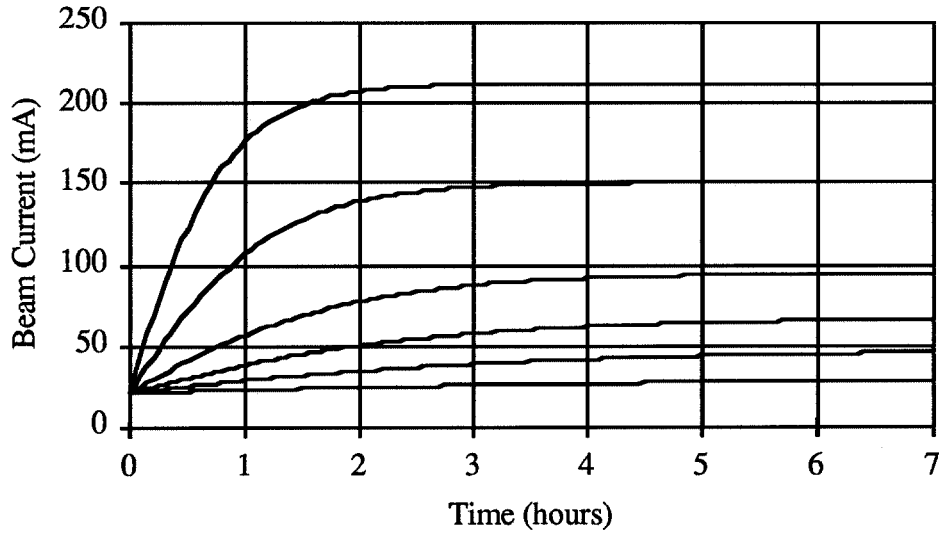


Figure 5.4: Simulation results of the evolution of the instantaneous beam current of the recycled antiprotons. The different curves correspond to different initial stochastic cooling times in the order 5 (bottom), 2, 1, 0.5, 0.2, and 0.1 (top) hours.

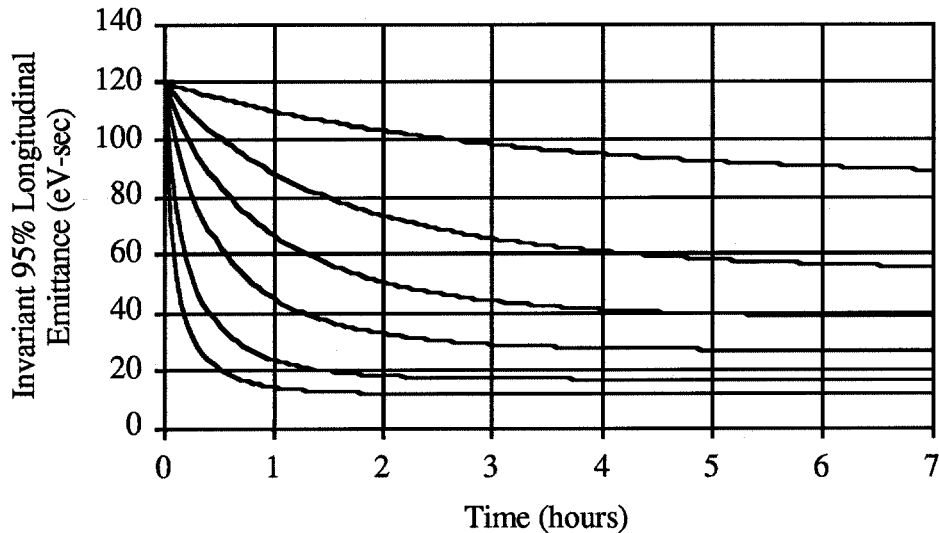


Figure 5.5: Simulation results of the time evolution of the invariant 95% longitudinal emittance of the recycled antiprotons. The different curves correspond to different initial stochastic cooling times in the order 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom) hours.

Of course the real figure of merit describing the effectiveness of the momentum cooling in the Recycler is the number of antiprotons per eV-sec. Given that the initial intensity for each of the 36 antiproton bunches must be $6.6 \times 10^{10} / 0.9 = 7.3 \times 10^{10}$ (assuming a 90% acceleration efficiency), in order to achieve 1.5 eV-sec bunches assumed in figure 5.2 the phase density would have to be $4.9 \times 10^{10} / \text{eV-sec}$ for the entire antiproton stack.

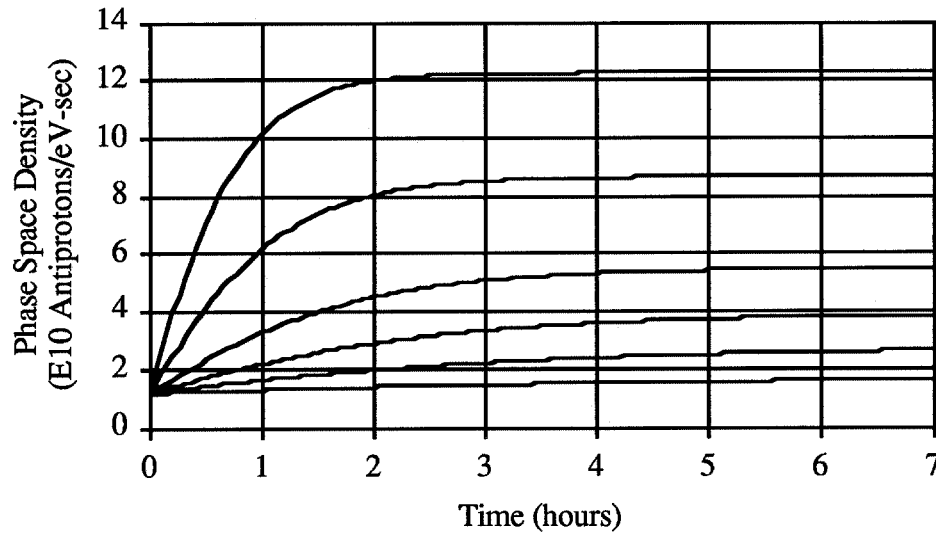


Figure 5.6: Simulation results of the time evolution of the longitudinal phase space density of the recycled antiprotons. The different curves correspond to different initial stochastic cooling times in the order 5 (bottom), 2, 1, 0.5, 0.2, and 0.1 (top) hours.

5.2. Stacking Antiprotons from the Accumulator

It is anticipated that transfers of antiprotons from the Accumulator will occur at an interval of 1 hour. Assuming a stacking rate of 20×10^{10} antiprotons/hour, this means that 20×10^{10} antiprotons are anticipated each hour. The momentum spread of this beam is expected to be approximately 1.5 MeV in a pulse 1.5 μsec long (for an invariant 95% longitudinal emittance of 9 eV-sec). This beam is also expected to have a transverse 95% invariant emittance of 10π mmmr.

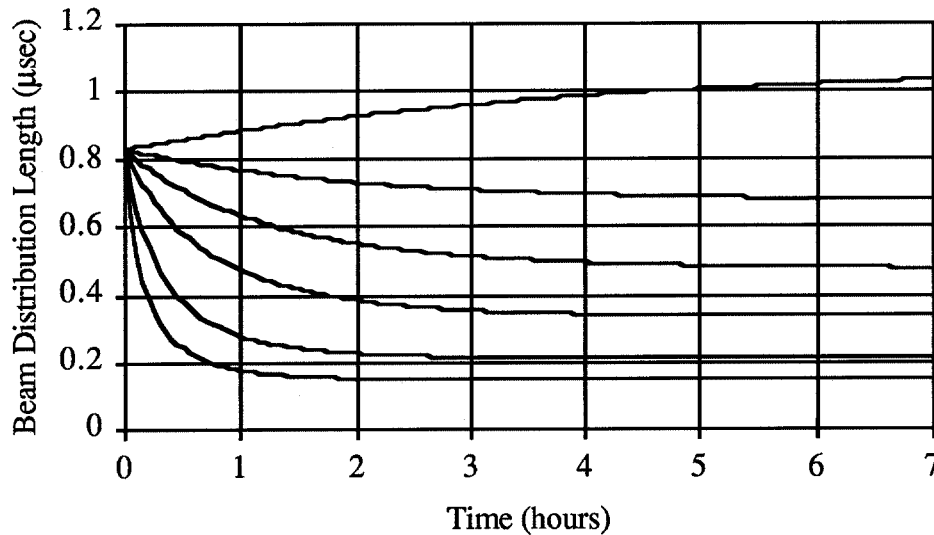


Figure 5.7: Simulation results of the time evolution of the beam distribution length of a stacked antiproton batch. The different curves correspond to different initial stochastic cooling times in the order 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom) hours.

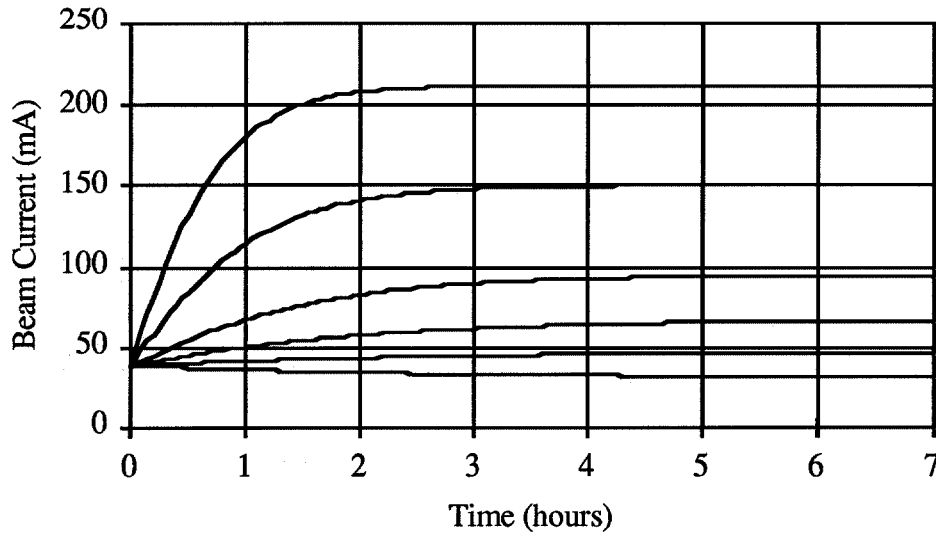


Figure 5.8: Simulation results of the time evolution of the beam current of a stacked antiproton batch. The different curves correspond to different initial stochastic cooling times in the order 5 (bottom), 2, 1, 0.5, 0.2, and 0.1 (top) hours.

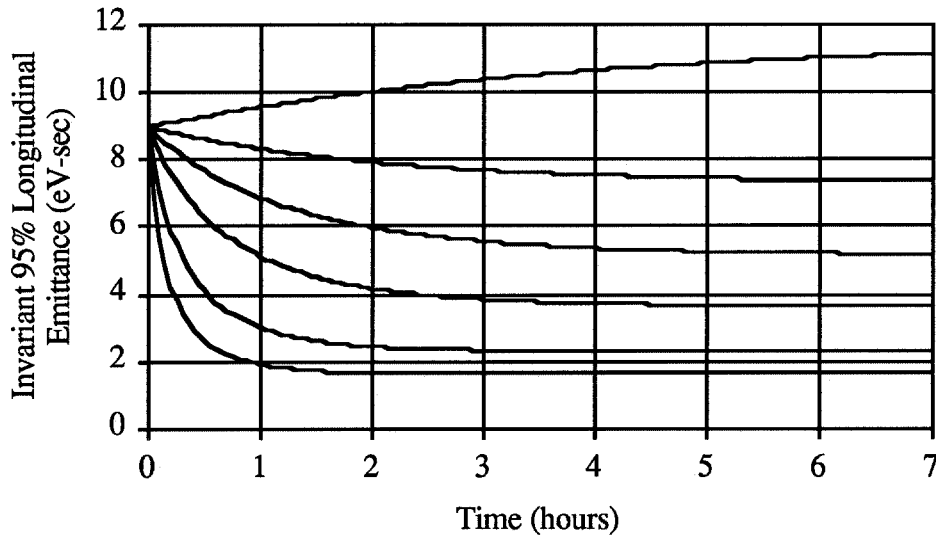


Figure 5.9: Simulation results of the time evolution of the invariant 95% longitudinal emittance of a stacked antiproton batch. The different curves correspond to different initial stochastic cooling times in the order 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom) hours.

Just after each transfer from the Accumulator, the beam distribution length is compressed so as to produce the same rms energy spread of 2.7 MeV that was used with the recycled antiprotons. Just as with the recycled beam, the momentum spread of the stacked antiprotons from the Accumulator will be maintained at a constant value by continued pulse compression.

Assuming the same cooling systems as the recycled beam (0.1 to 5 hour cooling times on 148×10^{10} particles uniformly distributed around the entire ring with an rms energy

spread of 2.7 MeV) the evolution of the stacked beam distribution can be calculated similar to the above recycled beam calculations. Figures 5.7 through 5.10 contain the results of this simulation. Because of the higher initial instantaneous beam current of the stacked beam, the longest initial cooling time of 5 hours is not sufficient to overcome the intrabeam scattering.

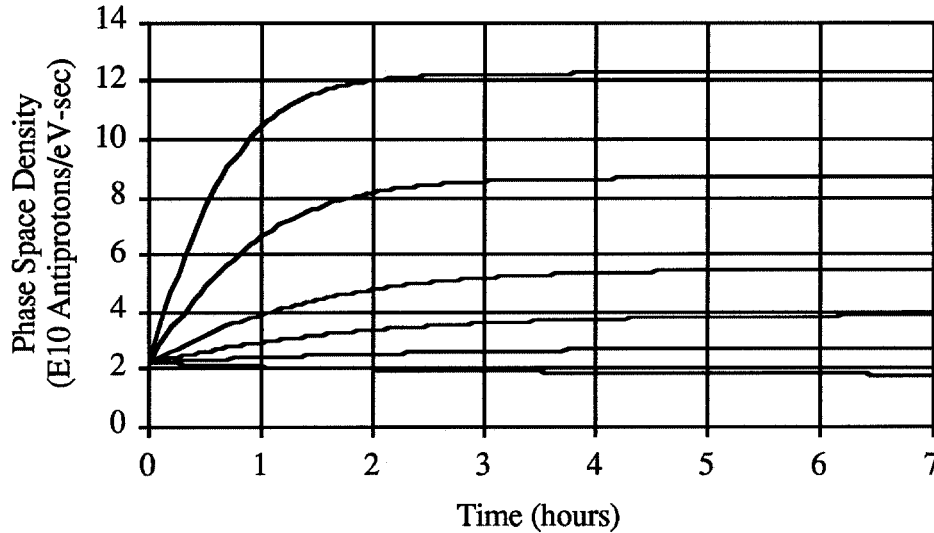


Figure 5.10: Simulation results of the time evolution of the invariant 95% longitudinal emittance of a stacked antiproton batch. The different curves correspond to different initial stochastic cooling times in the order 5 (top), 2, 1, 0.5, 0.2, and 0.1 (bottom) hours.

5.3. Integrated Stacking Scenario

After the cooled antiprotons are injected into the Tevatron and only the recycled beam is in the Recycler, batch #7 is injected into the Recycler and merged with the recycled beam. This new distribution is called the core. The core is adiabatically expanded around the ring circumference until an rms momentum spread of 2.7 MeV is achieved. At this point little or no gap is remaining in the Recycler distribution. This situation is sketched in figure 5.11.

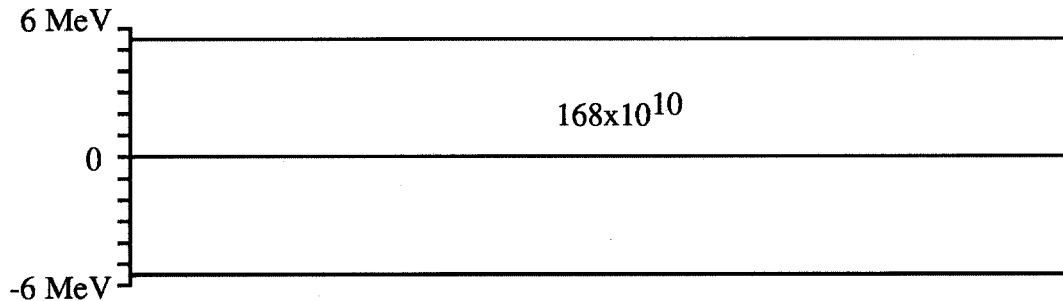


Figure 5.11: Phase space sketch of the initial state of the Recycler core (composed of the recycled beam and batch #7 from the Accumulator) just after initial debunching. In the figure one full azimuth of the Recycler ring is shown on the X-axis while the 2 sigma phase space density contour is shown in the momentum deviation or Y-axis. The total antiproton intensity of this distribution is also shown.

Table 5.1: Specifications for the momentum cooling system assumed in the calculations in this section.

Parameter	Value
Minimum Momentum Half Aperture (MeV)	5.4
Beam Current (mA)	21
Noise Power to Signal Power Ratio U	negligible
RMS Momentum Spread (MeV)	2.7
Momentum Cooling Time (hours) $[1/\sigma_e d\sigma_e/dt]^{-1}$	0.5

In this section it is assumed that the cooling system generates a 30 minute cooling time at the Recycler beam current of 21 mA when the rms energy spread is 2.7 MeV (the beam distribution for the recycled beam alone). The purpose of this particular example is to show why this is a reasonable cooling time to aim for Table 5.1 summarizes these stochastic cooling specifications.

The initial core antiprotons are cooled with the momentum cooling time of 34 minutes (the increase from 30 to 34 minutes due to the extra particles from batch #7). Keeping the energy spread constant by compressing the beam distribution with the barrier RF voltage pulse system, the length of the distribution shrinks from the full ring circumference (11.126 μ sec) to 4.7 μ sec in the first hour. Because the instantaneous beam current has increased from 21 mA to 58 mA, the cooling rate has increased from 34 minutes to 1.4 hours. Similarly, the intrabeam scattering growth time decreased from 9.5 hours to 3.7 hours. The 95% invariant longitudinal emittance started out at 129 eV-sec for a phase space density of $1.3 \times 10^{10}/\text{eV-sec}$, and ended up after the one hour of cooling at 50 eV-sec and $3.3 \times 10^{10}/\text{eV-sec}$.

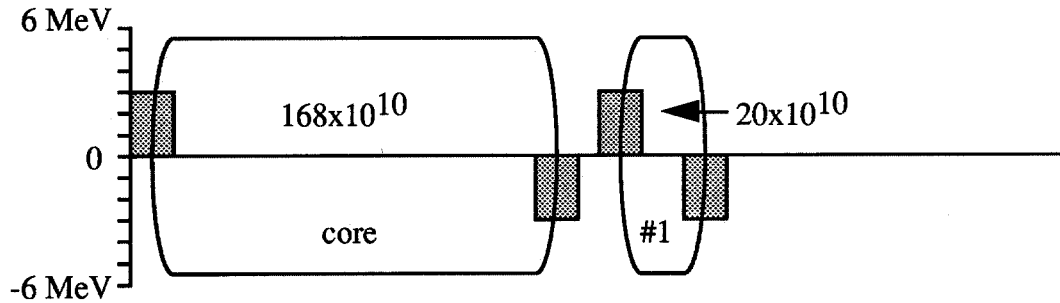


Figure 5.12: Recycled beam distribution (left) and newly injected antiprotons from the Accumulator (right) one hour after the beginning of a Tevatron Collider store. The 1 kV 0.5 μ sec long RF voltage pulses (gray rectangles) are used to compress both beam distributions in order to maintain an rms momentum spread of 2.7 MeV. Again, the 2 sigma phase space density contours are shown.

Assuming that antiproton transfers from the Accumulator ring are occurring once an hour, at this point the first batch of beam from the Accumulator is injected into the Recycler. Figure 5.12 contains a sketch of the Recycler phase space after that transfer. The injected batch has been compressed so that the rms momentum spread of its distribution is also 2.7 MeV. But because its phase space density is only $2.2 \times 10^{10}/\text{eV-sec}$, direct absorption of the injected batch into the recycled distribution will slightly dilute the core distribution. The absorption is carried out by adiabatically reducing the voltage of the intermediate barrier RF pulses until the distributions are merged.

This process is repeated another 5 times. At that batch #6 from the Accumulator has been injected and absorbed into the core. The remaining 1.5 hours until the beam is injected into the Tevatron Collider, the core is cooled. See table 5.2 for the beam intensity, distribution length, invariant 95% longitudinal emittance, and phase space density of the beams at all steps in the stacking process.

Table 5.2: Summary of the beam distribution parameters during one full antiproton stacking period.

Time (hours)	Beam	Intensity (E10)	Length (μ sec)	Emittance (eV-s)	Density (E10/eV-s)
0	Recycled	148	10.2	120	1.2
	Batch #7	20	0.83	9	2.2
	Core	168	11.1	129	1.4
1	Core	168	4.7	50	3.3
	Batch #1	20	0.83	9	2.2
	Core	188	5.5	59	3.2
2	Core	188	3.9	42	4.4
	Batch #2	20	0.83	9	2.2
	Core	208	4.7	51	4.1
3	Core	208	3.9	43	4.9
	Batch #3	20	0.83	9	2.2
	Core	228	4.8	52	4.4
4	Core	228	4.2	45	5.0
	Batch #4	20	0.83	9	2.2
	Core	248	5.0	54	4.6
5	Core	248	4.5	48	5.1
	Batch #5	20	0.83	9	2.2
	Core	268	5.3	57	4.7
6	Core	268	4.8	52	5.2
	Batch #6	20	0.83	9	2.2
	Core	288	5.6	61	4.8
7.5	Core	288	5.0	55	5.3

Because a conservative stacking rate of 20×10^{10} /hr stacking rate was assumed, the final beam intensity of 288×10^{10} antiprotons is roughly 10% more than the required number of $36 \times 7.3 \times 10^{10} = 263 \times 10^{10}$. The total phase space density divided into 36 antiproton bunches yields a per bunch longitudinal emittance of 1.5 eV-sec, consistent with figure 5.2 and a 10% acceleration dilution factor (assuming that coalescing is not utilized and the 1.5 eV-sec distribution is accelerated through Main Injector transition with the 2.5 MHz RF system).

The final core distribution had an instantaneous beam current of 92 mA. The stochastic cooling rate at this current is 2.17 hours. On the other hand, the intrabeam scattering growth rate is 2.30 hours. Therefore, the system specified in table 5.1 is just sufficient to service the antiproton stacking needs of Run II.

5.4. Comparison with Debunched Stacking

If the final distribution was fully debunched the beam current would be 41 mA and the rms energy spread 1.2 MeV. In figure 5.13 the calculated intrabeam scattering growth rate is displayed at this beam current. Note that at an energy spread of 1.2 MeV the growth rate is slightly larger than 2 inverse hours, making the growth time a little shorter than 30 minutes. Given that the momentum spread is smaller and beam current

twice as high as the specifications in table 5.1, it is clear that the same cooling system assumed above could not possibly achieve the same final beam emittance. Clearly the use of the barrier buckets yields a substantial cooling performance improvement.

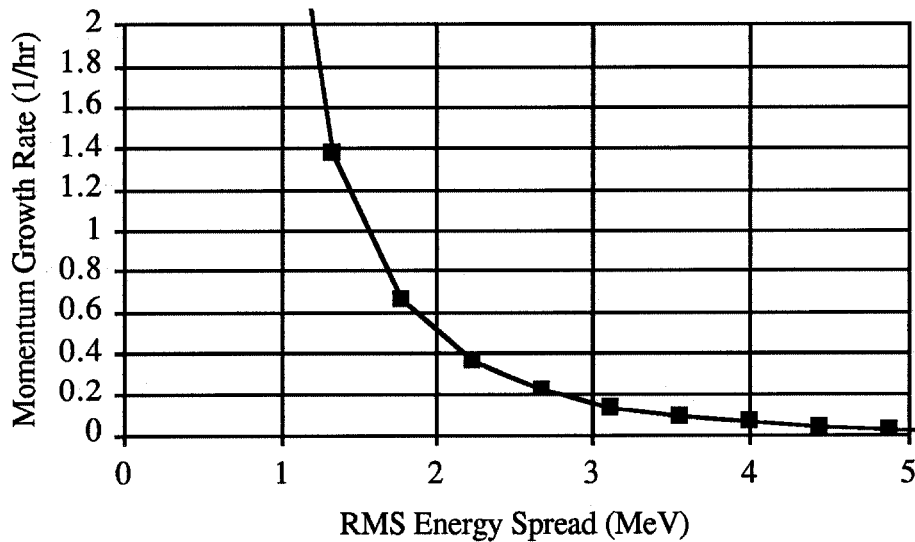


Figure 5.13: Colestock prediction of the momentum growth rate at 41 mA of beam current in the Recycler ring at a transverse emittance of 10π mm²·mrad.

6. Discussion

Because of the novel nature of this approach to momentum cooling, a number of objections may be raised. In this section a number of these issues are addressed in advance.

6.1. Will this scheme suffer from coherent power generation like the Tevatron?

The problematic experience with the Tevatron bunched beam stochastic cooling system is a valid source of concern when contemplating the barrier bucket modified momentum cooling scenario outline in this paper. On the other hand, it should be pointed out that the scenario discussed in the paper is NOT bunched beam stochastic cooling, since the synchrotron frequency spread is equal to the synchrotron frequency itself.

The experience in the Tevatron was that revolution harmonics, as high as $h=100,000$, were anomalously powerful. As a result, the gain of the system necessary for cooling the beam completely saturates the downstream, high level amplifiers.

This phenomenon was also observed in the CERN AC ring (Pasquinelli, private communication). They found that the power in the revolution harmonics could be suppressed with the momentum cooling system. As long as a situation is generated where the anomalous power is not present and the cooling system can be turned on without saturation, this power can be controlled.

In the Recycler ring, there is always a point at which the beam is completely debunched, allowing the cooling system to be turned on. Therefore, it is anticipated that beam phase space manipulations can be created which control this feature of bunched beams.

6.2. What if the recycled beam longitudinal emittance is larger than anticipated?

The largest longitudinal emittance which can be stored in the Tevatron is approximately 6 eV-sec. Therefore, it is potentially possible to transfer 250 eV-sec worth of beam to the Recycler.

In order for the recycled and cooled beam to coexist in the Recycler before injection of the cooled beam into the Tevatron, the recycled beam distribution be less than 6 μ sec long. The maximum longitudinal emittance which can be contained in this interval using the 2 kV RF pulses is described by the equation

$$A = \frac{8}{3} \Delta E_{1/2} T \quad (6.1)$$

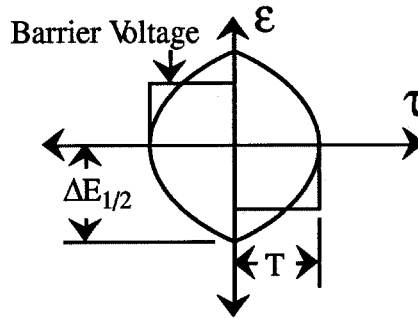


Figure 6.1: Sketch of the maximal bucket area in a barrier bucket formed by rectangular RF pulses.

Since T is 3 μ sec, the bucket half height must be 31.25 MeV in order to contain the 250 eV-sec of beam. Using equation (3.3) the required voltage is 1.8 kV, just enough.

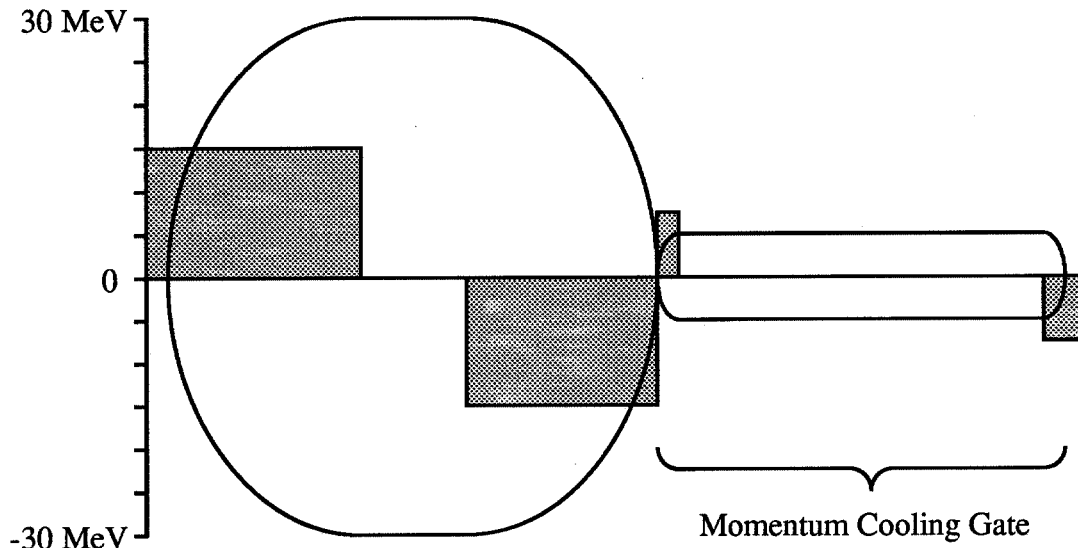


Figure 6.2: Sketch of the longitudinal phase space distribution in which 5 μ sec of azimuth was used for cooling while the rest of the antiprotons are stored separately in a large energy spread reservoir.

Once the cooled antiprotons have been injected into the Tevatron, the recycled antiprotons can be adiabatically expanded. At 250 eV-sec, the rms energy spread for a

completely debunched beam would be 5.6 MeV, requiring a cooling system with a momentum acceptance of 12 MeV. If such a cooling system does not exist, what can be done? The answer is to cool only a fraction of the distribution at a time.

The intrabeam scattering growth time for the compressed recycled antiprotons is 470 hours. Therefore, this distribution is basically stationary on the time scale relevant for cooling the recycled beam. By slowly lowering the barrier RF pulses, the empty 5 μ sec of the Recycler is filled with beam up to an rms energy spread of 2.7 MeV. The cooling system is then turned on and gated just around that 5 μ sec. As the lower energy spread antiprotons are cooled, the barrier pulses are lowered to bring in more antiprotons, keeping the rms energy spread constant. Figure 6.2 contains a phase space sketch of this arrangement.

In this scenario the phase space density of the recycled antiprotons is $0.51 \times 10^{10}/\text{eV}\cdot\text{sec}$. The initial intensity in the 5 μ sec cooling zone is 28×10^{10} , corresponding to a beam current of 9.0 mA. Therefore, using the cooling system specified in chapter 5, the initial cooling time is 13 minutes. Using a simulation similar to the one used in chapter 5, the evolution of the beam intensity in the cooling zone is estimated. The results of this calculation is shown in figure 6.3, in which it is shown that it takes approximately 3 hours to cool the recycled antiprotons.

In the mean time, two transfers from the Accumulator must take place. As recycled antiprotons leave the barrier bucket to enter the cooling zone, the barrier bucket is constantly compressed. This leaves adequate space for injection of the stacked antiprotons. The stacked antiprotons can be either maintained in a separate barrier bucket or merged with the antiprotons in the cooling zone.

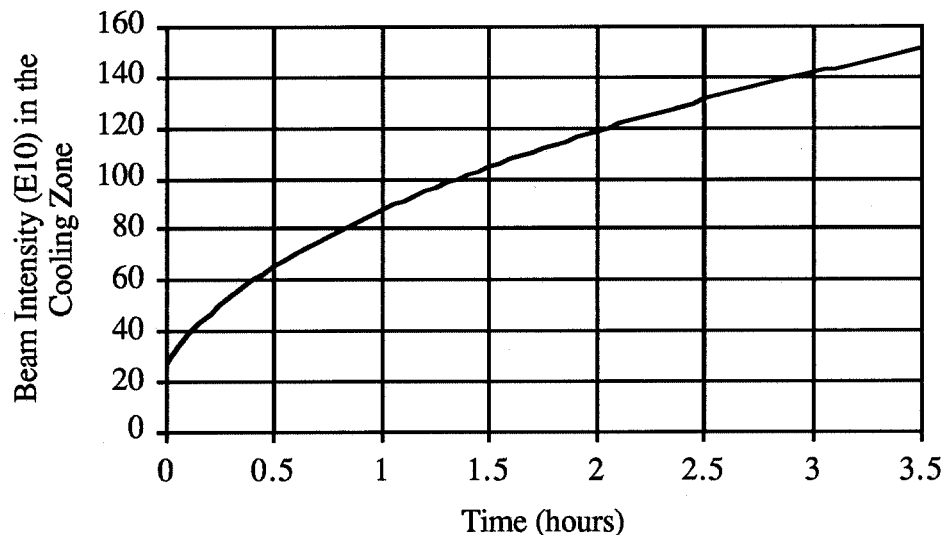


Figure 6.3: Time evolution of the antiproton intensity in the 5 μ sec cooling zone assuming the same cooling system used in chapter 5.

6.3. If the store is lost immediately, how long is the recycled beam cooling time?

One of the impressive benefits of the Recycler ring is the ability to recover gracefully from premature and early Tevatron store losses. Without the Recycler ring, the time before the Tevatron can be reloaded at half of the nominal peak luminosity is 3.5 hours (half of the nominal stacking time assuming the same store length as with the Recycler ring). With the Recycler ring in existence, the time is determined by the ability of the cooling system to shrink the phase space of beam recycled from the previous store down to $1.5 \times 36 = 54 \text{ eV}\cdot\text{sec}$. From figure 5.5 it is evident that this emittance is achieved within

45 minutes. Since it takes more than this time to understand the failure and reestablish Tevatron operations, this is more than fast enough.

Assuming this new store stays in, how long does it have to be stay in to regain the nominal initial luminosity? Since the luminosity is lower, the rate at which antiprotons are consumed is smaller. Approximately 80×10^{10} antiproton would be recycled after 12 hours. This store duration gives the Accumulator an extra 4 hours to generate the balance of 80×10^{10} needed to complete the necessary stack size. This is a far superior method of recovering from lost Tevatron stores than available to operations in Run I and before.

7. Conclusions

It has been shown that the use of barrier buckets to maintain a constant, maximal energy spread significantly improves the momentum cooling capabilities of the Recycler ring.

The next step is to generate designs for both a filter and Palmer stochastic cooling system for the Recycler ring which meets the specifications listed in table 5.1.